Resonance $f_0(1500)$: Is it a scalar glueball ?

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Abstract

The ratios of partial widths for the decay of a glueball into two pseudoscalar mesons are calculated under the assumption that the production of light quark pairs ($u\bar{u}, d\bar{d}, s\bar{s}$) in soft gluon-induced reactions goes on within universal symmetry breaking. Parameter of the violation of flavour symmetry is fixed by the central hadron production data in high energy hadron collisions and/or by the ratios of radiative decay amplitudes $J/\Psi \to \gamma\eta/\gamma\eta'$ and $J/\Psi \to \gamma\phi\phi/\gamma\omega\omega$. The ratios of coupling constants $glueball \to \pi\pi, K\bar{K}, \eta\eta, \eta\eta'$ which are calculated with this parameter coincide reasonably with those of $f_0(1500)$, supporting an idea about glueball nature of $f_0(1500)$.

Resonance $f_0(1500)$, which has been discovered by Crystal Barrel Collaboration in the simultaneous analysis of the reactions $p\bar{p}$ (at rest)$\to \pi^0\pi^0\pi^0$ and $\eta\eta\pi^0$, was immediately considered as a candidate for the lowest scalar glueball [1]:

(i) Its mass is near the value predicted by the lattice-QCD calculations [2];

(ii) From the point of view of $q\bar{q}$-systematics, this resonance looks as a superfluous one (the detailed discussion can be found, for example, in refs. [3, 4]);

(iii) In the gluon-rich reaction, $J/\Psi \to \gamma + 4\pi$, a sharp peak is seen in the four-pion spectrum, which is compatible in mass and width with $f_0(1500)$; later the re-analysis of MARK-III data revealed its quantum numbers to be 0^{++} [5].

But additional arguments in favour of the glueball nature of $f_0(1500)$ are needed. Certain scepticism can be also extended on the arguments (i) and (ii). The matter is that the present lattice calculations of the glueball masses do not take properly into account quark degrees of freedom. Still, the mixture of glueball and neighbouring $q\bar{q}$ states can be significant: this mixture is not suppressed in accordance with the rules of $1/N$-expansion [6, 7] ($N = N_c = N_f$ is the number of colours and light flavours). An admixture of the $q\bar{q}$-components can shift the mass of the real glueball as compared to the pure

gluodynamic calculations. Moreover, the latest lattice-QCD result based on the nowadays larger statistics gives a substantially higher value for the mass of the pure glueball, $m(0^{++}) = 1740 \pm 50$ MeV [8].

Systematics of the $q\bar{q}$-mesons requires four states with the quantum numbers of the scalar glueball in the mass region 1000–1600 MeV [9]: two ground states of the $^3P_0 q\bar{q}$-nonet together with their radial excitations. There are candidates for these states, see refs. [9]–[11]. However, scalar resonances in the mass region 1100–1300 MeV have rather large widths: a distant location of the corresponding poles of the amplitude from the physical region allows one to be sceptical about their existence.

In ref. [12] the possibility to test glueball nature of $f_0(1500)$ by studying its partial widths has been emphasized. In this paper the ratios of couplings of $f_0(1500)$ to $\pi\pi, K\bar{K}, \eta\eta'$ and $\eta\eta'$ have been calculated. The consideration presented in this paper is modified, as compared to that of ref. [12], in two points:

(i) The diagrams for a glueball decay into two pseudoscalar $q\bar{q}$-mesons are selected according to $1/N$-expansion rules; the leading diagrams are taken into account only. This reduces the number of unknown parameters.

(ii) The flavour-symmetry violation parameter, λ, is fixed by the ratio of strange and non-strange hadrons produced in the central region of high energy hadron collisions and/or by the branching ratios of the radiative decays $J/\Psi \to \gamma\eta/\gamma\eta'$ and $J/\Psi \to \gamma\phi\phi/\gamma\omega\omega$.

This gives explicit values for the ratios of coupling constants $glueball \to \pi\pi, K\bar{K}, \eta\eta, \eta\eta'$ which coincide rather reasonably with those of $f_0(1500)$.

Two types of processes determine the glueball decay into two pseudoscalar mesons [12, 13]. They are shown in Figs. 1a and 1b or more schematically in Figs. 1c and 1d. According to $1/N$-expansion rules, the main contribution is given by the diagram of Fig.1c, while the contribution of the process of Fig. 1d is suppressed by the factor $1/N$. Indeed, the coupling constants which determine the process of Fig.1c have the following order of magnitudes: $g_{GL}(glueball \to q\bar{q}) \sim 1/N$ and $g_m(meson \to q\bar{q}) \sim 1/\sqrt{N}$. So, the vertex of Fig.1c is of the order of $g_{GL}\, g_m^2\, N_c \sim 1/N$. The vertex of the diagram of the Fig.1d is determined by additional couplings $\widetilde{g}_{GL}(glueball \to gg) \sim 1/N$ and $g(g \to q\bar{q}) \sim 1/\sqrt{N}$, so it is of the order of $\widetilde{g}^4_{GL}\, g_m^2\, N_c^2 \sim 1/N^2$. Let us note that quark content of the produced mesons in the diagrams of Figs.1c and 1d is fixed; thus, quark loops in these diagrams do not generate the enlarging factor N_f [7]. Below the contribution of the process of Fig.1c is taken into account only; the next-to-leading contribution (Fig.1d) is neglected.

In the process of Fig.1c (or Fig.1a), two $q\bar{q}$-pairs are produced by soft gluons, and this production goes with flavour symmetry violation. Clear indication on this violation is seen in other gluon-rich processes. Central production of hadrons in the hadron collisions at high energies is determined by the following process: the gluons of the pomeron create $q\bar{q}$-pairs which are then transformed into hadrons. Fig. 2a provides an example of a diagram which describes the $q\bar{q}$ production cross section. Experimental data at high and

superhigh energies confirm the suppresion of the $s\bar{s}$-production:

$$u\bar{u} : d\bar{d} : s\bar{s} = 1 : 1 : \lambda. \tag{1}$$

The production probability factor, λ, is related to the directly produced hadrons (i.e. to the hadrons which are not resonance decay product); it is equal to $\lambda = 0.4 - 0.5$ (see [14] and references therein).

Branching ratios for the radiative decays $J/\Psi \to \gamma\eta$ and $\gamma\eta'$ give us another evidence for the flavour symmetry breaking with the same parameter λ as in the central hadron production. Hadron production in the radiative J/Ψ-decay is determined by the $c\bar{c}$-annihilation into two gluons [15] with the subsequent production of the light-quark $q\bar{q}$-pair (see Fig. 2b). The process of Fig. 2b leads to the following ratio for the decay couplings:

$$\frac{g(J/\Psi \to \gamma\eta')}{g(J/\Psi \to \gamma\eta)} = \frac{\sqrt{2}\sin\Theta + \sqrt{\lambda}\cos\Theta}{\sqrt{2}\cos\Theta - \sqrt{\lambda}\sin\Theta}. \tag{2}$$

Here Θ is the mixing angle for $n\bar{n} = (u\bar{u}+d\bar{d})/\sqrt{2}$ and $s\bar{s}$ components in η and η', namely, $\eta = \cos\Theta n\bar{n} - \sin\Theta s\bar{s}$ and $\eta' = \sin\Theta n\bar{n} + \cos\Theta s\bar{s}$. The branching ratios $\gamma\eta$ and $\gamma\eta'$ are equal to $B(\gamma\eta) = (8.6 \pm 0.8) \cdot 10^{-4}$ and $B(\gamma\eta') = (4.3 \pm 0.3) \cdot 10^{-3}$ [9], so the ratio of the decay amplitudes, Eq.(2), is equal to 2.02 ± 0.23. This gives $\lambda = 0.48 \pm 0.09$.

The processes $J/\Psi \to \gamma\phi\phi$ and $J/\Psi \to \gamma\omega\omega$ present non-resonance production of two $q\bar{q}$-mesons. They are shown in Fig. 2c. Supposing "ideal" $\phi - \omega$ mixing , $\phi = s\bar{s}$ and $\omega = n\bar{n}$, one has the following ratio for the decay couplings:

$$\frac{g(J/\Psi \to \gamma\phi\phi)}{g(J/\Psi \to \gamma\omega\omega)} = \lambda. \tag{3}$$

Corresponding branching ratios, $B(\gamma\phi\phi) = (4.0 \pm 1.2)10^{-4}$ and $B(\gamma\omega\omega) = (15.9 \pm 3.3)10^{-4}$ [9], give $\lambda \simeq 0.5$ again. Thus, in the radiative J/Ψ-decays the strange-quark production probability factor, λ, is the same as in the high-energy central production, supporting an idea of universality of the parameter λ in soft gluonic processes.

Now let us return to the discussion of the glueball decay into two pseudoscalar mesons. The decay coupling constants, being determined by the process of Fig.1c, differ only in factors which depend on the quark content of pseudoscalar mesons and the suppression parameter λ. These factors squared are presented in Table 1. As a result, the partial width ratios, corrected in phase spaces $\gamma^2 = \Gamma/\phi$, are equal to

$$\gamma^2(\pi\pi) : \gamma^2(K\bar{K}) : \gamma^2(\eta\eta) : \gamma^2(\eta\eta') : \gamma^2(\eta'\eta') =$$

$$1 : \frac{4}{3}\lambda : \frac{1}{3}(\cos^2\Theta + \lambda\sin^2\Theta)^2 : \frac{2}{3}(1-\lambda)^2\sin^2\Theta\cos^2\Theta : \frac{1}{3}(\sin^2\Theta + \lambda\cos^2\Theta)^2. \tag{4}$$

With $\Theta = 37°$ [9] and $\lambda = 0.4$, we have for the righthand side of Eq. (3):

$$1 : 0.53 : 0.20 : 0.06 : 0.13. \tag{5}$$

These ratios are in a reasonable agreement with nowadays partial width data for $f_0(1500)$ obtained in the $p\bar{p}$-annihilation at rest: $\gamma^2(K\bar{K})/\gamma^2(\pi\pi) = 0.49 \pm 0.16$ [16]; $\gamma^2(\eta\eta)/\gamma^2(\pi\pi) =$

0.27 ± 0.11 [12], 0.23 ± 0.09 [17]; $\gamma^2(\eta\eta')/\gamma^2(\pi\pi) = 0.19 \pm 0.08$ [12], 0.33 ± 0.16 [17]. This allows us to consider $f_0(1500)$ as a good candidate for glueball. However, more precise extraction of branching ratios is definitely required. The main problem in finding partial widths is an interference of the $f_0(1500)$ signal with the background, which causes additional systematic errors. For example, another parametrization of the background [18] leads to the ratio $\gamma^2(\eta\eta)/\gamma^2(\pi\pi)$ twice as small as that of ref. [12]. This emphasizes a necessity of further study of the $f_0(1500)$ branching ratios, especially with other possible backgrounds, namely, in different reactions or at different $p\bar{p}$-energies.

In ref. [19] the glueball origin of $f_J(1710)$ has been supposed. However, the measured ratio of the decay probabilities $f_J(1710) \to \pi\pi/K\bar{K}$ is of the order of 0.3 [9,20] which disagrees strongly with the idea of suppression of the strange quark production in gluonic processes (see Table 1 for $\pi\pi/K\bar{K}$ ratio).

The factors given in Table 1, which describe the transition *gluons* $\to$ *two* $q\bar{q}$ *mesons*, can be applied not only to the glueball decay. As was mentioned above, the same factors give relative probabilities for the non-resonance production of the two $q\bar{q}$-mesons in the radiative J/Ψ-decay (see Fig. 2c). Therefore, these factors can be used as a test of the gluonic nature of resonances produced in the radiative J/Ψ-decay, because the glueball decay products as well as the background events obey the relations given in Eq. (4), while the production via $q\bar{q}$-resonance should disturb these relations.

In conclusion, the high energy central production data give a clear evidence that light quarks in soft gluonic processes are produced with the flavour symmetry violation: the strange quark production is suppressed. The radiative decay ratios $J/\Psi \to \gamma\eta/\gamma\eta'$ and $\gamma\phi\phi/\gamma\omega\omega$ reveal the same suppression factor in the transition *gluons* $\to q\bar{q}$ as the high energy production data. Coupling constants for the glueball decay into two $q\bar{q}$-mesons are calculated using the idea of universality of the flavour symmetry violation in the production of soft $q\bar{q}$-pairs by gluons. These coupling constants are in reasonable agreement with the Crystal Barrel data for the decay ratios of $f_0(1500)$ into two pseudoscalar mesons, thus arguing in favour of glueball nature of $f_0(1500)$. The obtained ratios can be also used in the radiative J/Ψ-decays to test the glueball origin of the produced resonances.

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Table 1. Coupling constants squared for the glueball decay

Decay channel	Coupling squared	Identity particle factor
$\pi^0\pi^0$	1	$1/2$
$\pi^+\pi^-$	1	1
K^+K^-	λ	1
$K^0\bar{K}^0$	λ	1
$\eta\eta$	$(\cos^2\Theta + \lambda\sin^2\Theta)^2$	$1/2$
$\eta\eta'$	$(1-\lambda)^2\sin^2\Theta\cos^2\Theta$	1
$\eta'\eta'$	$(\sin^2\Theta + \lambda\cos^2\Theta)^2$	$1/2$

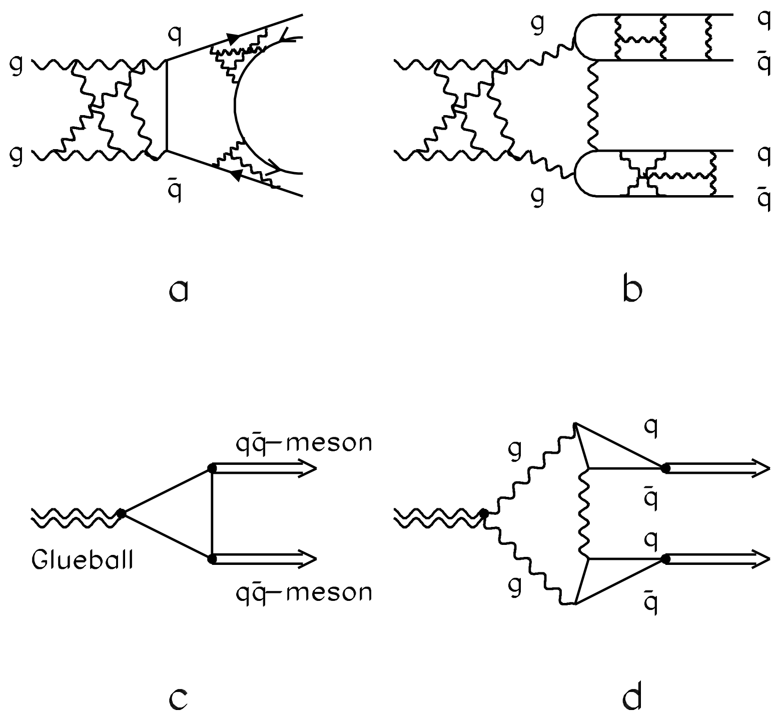

Fig. 1. Production of $q\bar{q}$-pair in the decay *glueball* $\rightarrow$ *two* $q\bar{q}$ *mesons*.

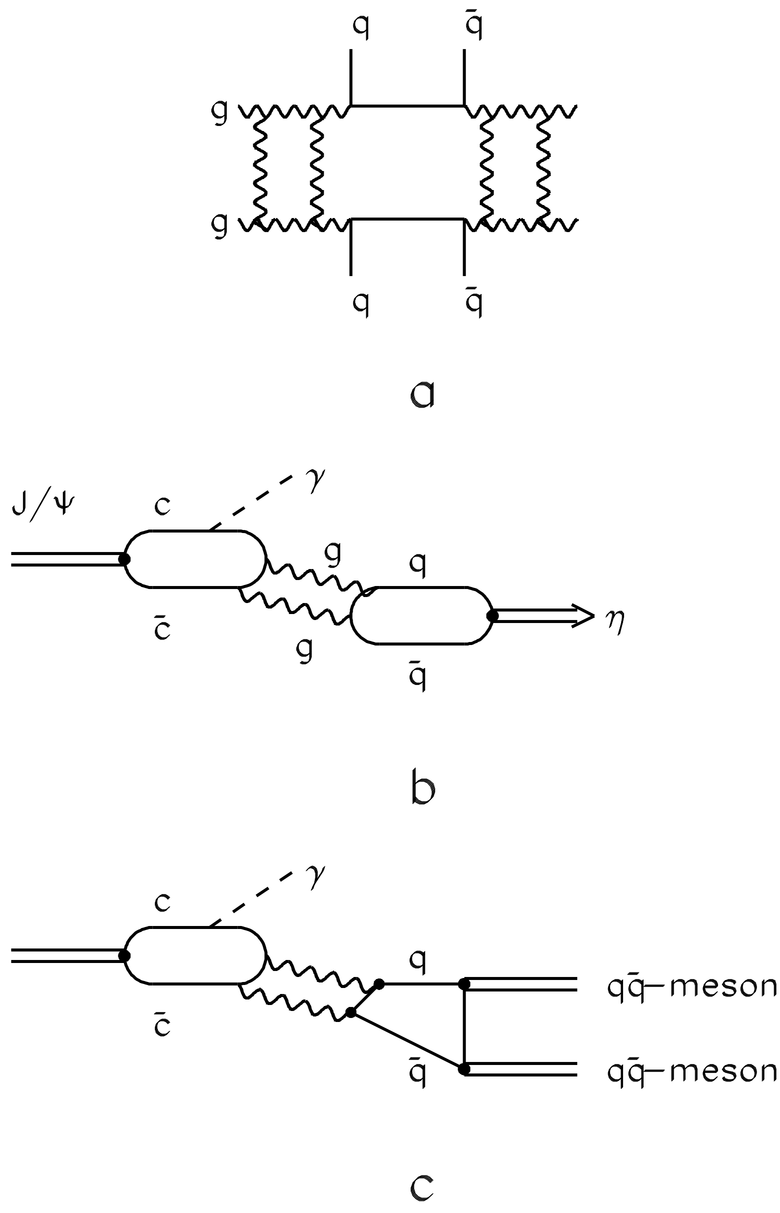

Fig. 2. Production of $q\bar{q}$-pairs in the gluon ladder of the pomeron (a), and in the radiative J/Ψ-decay (b,c).